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Multispectral Thermal Imager – Overview

W. Randy Bell and Paul G. Weber

On behalf of the MTI Team at Sandia and Los Alamos National Laboratories and the Savannah River Technology Center.

The Multispectral Thermal Imager, MTI, is a research and development project sponsored by the United States Department of Energy. The primary mission is to demonstrate advanced multispectral and thermal imaging from a satellite, including new technologies, data processing and analysis techniques. The MTI builds on the efforts of a number of earlier efforts, including Landsat, NASA remote sensing missions, and others, but the MTI incorporates a unique combination of attributes. The MTI satellite was launched on 12 March 2000 into a 580 km X 610 km, sun-synchronous orbit with nominal 1 am and 1 pm equatorial crossing times. The Air Force Space Test Program provided the Orbital Sciences Taurus launch vehicle. The satellite has a design lifetime of a year, with a goal of three years. The satellite and payload can typically observe six sites per day, with either one or two observations per site from nadir and off-nadir angles. Data are stored in the satellite memory and down-linked to a ground station at Sandia National Laboratory. Data are then forwarded to the Data Processing and Analysis Center at Los Alamos National Laboratory for processing, analysis, and distribution to the MTI team and collaborators. We will provide an overview of the Project, a few examples of data products, and an introduction to more detailed presentations in this special session.

Keywords: Modeling, Analysis, System Design, Multispectral Imaging, Thermal Imaging, Calibration.

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I. INTRODUCTION

We begin with a brief summary of imaging sensors in space. This will provide the context within which to discuss the important point in phase space which is filled by the Multispectral Thermal Imager satellite. We then cover some of the history which led to the funding of MTI as a free-flying satellite system. Following this, we briefly summarize the main elements of the MTI design and operations. Other papers in this session will provide much more detailed information on particular attributes.

2. HISTORICAL PERSPECTIVE AND CONTEXT FOR MTI

The history of observation of the Earth from space for civilian applications started in 1972 with the launch of the first of the Landsat series of satellites, which continues uninterrupted to the present (for a chronology to 1998, see Reference 1.) The Landsat mission is to provide timely information on all of the Earth's land areas and surrounding coastal regions., with modest spatial resolution. The main instrument on Landsat is the Enhanced Thematic Mapper, which has seven spectral bands: one with 60-meter (or 120-meter) spatial resolution in the long wave infrared, and six in the visible and near-infra-red with 30-meter resolution. The Landsat-7 also has a 15-meter resolution visible light panchromatic band. Launch dates for Landsat were 1972, 1975, 1978, 1982, 1984, 1993 (launch failure) and 1999, with Landsat 5 and Landsat 7 presently operational and providing unmatched continuity of global data.

The Land Remote Sensing Policy Act of 1992 directs Landsat Program Management (NASA and the USGS) to "assess options for a satellite system to succeed Landsat 7. The Act lays out four system development and management options for assessment: (1) private sector funding and management; (2) an international consortium; (3) funding and management by the United States Government; or (4) a cooperative effort between the United States Government and the private sector. A preference for the private sector option is expressed in the Act. NASA and the USGS are jointly exploring these options at this time. The agencies clearly recognize the preference for strong private sector involvement and are exploring strategies that ensure the continuity of the Landsat 7 mission from a privately managed satellite system. It is anticipated that the system will need to be in place by 2005 to 2006 time frame in order to maintain continuous seasonal data acquisitions to the EROS Data Center Archive." [2].

An ingredient in defining this new mission is the EO-1 satellite, launched on 21 November 2000 from Vandenberg Air Force Base, California. Three new land imaging instruments on EO-1 will collect multispectral and hyperspectral scenes over the course of its mission. The EO-1 multi-spectral sensor has ten spectral bands in the VNIR, with spatial resolution of thirty meters, plus a ten-meter resolution panchromatic band. As of the time of this writing, EO-1 is in formation with Landsat 7 and is currently taking about 6 to 8 concurrent images a day from its three instruments. All three instruments are performing nominally. The NASA Terra satellite is also in orbit very close to Landsat 7, with the goal of better understanding global environmental change[3]. The highest resolution imager on Terra is the ASTER with spatial resolution of 15 – 90 meters and wavelength bands from visible through long-wave infrared[4].

In 1986, the Centre Nationale d'Etudes Spatiales launched the first of a series of satellites named Systeme Probatoire d'Observation de le Terre (SPOT), with subsequent launches in 1990, 1993, and 1998. The SPOT imaging instruments, called High Resolution Visible (HRV) feature several twenty-meter multispectral visible bands and a 10-meter resolution panchromatic band[5].

In 1988, the India Space Research Organization launched the first of a series of Indian Remote Sensing satellites, with three subsequent launches. The instruments have several visible light spectral bands and spatial resolutions of tens of meters.

Several U. S. commercial entities are racing to provide high spatial resolution visible imagery. The IKONOS satellite was launched September 24, 1999 from Vandenberg Air Force Base, California. Since Jan. 1, 2000, when IKONOS imagery was first made available for sale to customers, the IKONOS satellite has logged milestones, including: collecting 24 million square kilometers of imagery, and creating 200,000 images, which are housed in Space Imaging's digital archive "[6]. Orbital Imaging Corporation (OrbImage) is constructing two high resolution satellites, dubbed Orbview 3 and Orbview 4, with spatial resolution of one meter panchromatic and four meters in four spectral bands in the visible and near-infra-red spectral regions [7]. EarthWatch, Inc. developed the QuickBird satellite system for one-meter spatial resolution imaging, but the satellite failed to reach proper orbit on 20 November 2000. The EarlyBird satellite, built for three-meter resolution panchromatic and fifteen-meter multispectral visible imaging, failed four days after launch in 1997 due to a power problem. QuickBird 2 is already in production at Ball Aerospace & Technologies Corp. in Boulder, Colorado, and EarthWatch intends to launch QuickBird 2 by mid 2001[8].

Indeed, the emergent commercial interests are sufficiently large to warrant a Commercial Remote Sensing Program within the Earth Science Enterprise at NASA[9]. The present global market for satellite images is estimated at $154M, compared to $2.4Billion for aerial photography; estimated growth is projected to a range of $420M to $2.5B by 2005 as quoted in The Economist magazine[10]

With all of this activity, one might ask whether there is a need for another remote sensing satellite? In the early 1990's, the answer to that question appeared to us to be a solid "Yes!" and, since March 2000, we have a system in orbit with some unique attributes. This paper discusses the basic science and applications drivers for the design of the Multispectral Thermal Imager satellite, funded by the U.S. Department of Energy (DOE)

The DOE goal for MTI is to demonstrate advanced multispectral and thermal imaging from a satellite, including sophisticated comprehensive modeling, new technologies, state-of-the-art calibrations, and advanced data processing and analysis techniques. Thus we view MTI as a technology demonstration, and not as a system which routinely provides data for a particular commercial, environmental, or other similar mission. The primary use of MTI is to collect data on a wide variety of sites, translate those data to retrieved physical quantities, and compare those to the actual scene attributes. That comparison is used to validate the physics based end-to-end models, analysis, and calibration techniques, and to advance remote sensing science for future applications.

Some of the sites are selected for the Department's own applications, and include high accuracy measurements on the surface of the Earth with concomitant improved understanding of industrial activity, land utilization, vegetation health, atmospheric conditions, etc. These goals were used to specify a system with very good spatial resolution (5-20 meter ground sampling distance, GSD), superb radiometric accuracy, and the ability to measure key atmospheric parameters at 20-meter GSD to allow unprecedented correction for atmospheric effects. Most elements that were required had been demonstrated individually at least once by a combination of Landsat and airborne sensors, most notably AVIRIS[11]. However, the very accurate calibrations required for this mission had not been demonstrated, and we formed a partnership with the National Institute of Science and Technology to develop part of that capability. We proceeded to design the required system for the DOE mission, but we also believed that a sub-set of the DOE goals might be achievable by significant augmentation of other systems, which led to an exploration of possible partnerships.

The superb continuity of data from the Landsat satellites is partly attributable to a philosophy of ensuring that each set of instruments is able to add consistently to the archive. For example, one finds very similar spectral bands, spatial resolutions, and spatial coverage (for some comparisons between the simultaneously operating Landsat 5 and Landsat 7, see Reference 12.). The Landsat calibrations appear to be stable through time, and within 5% of the actual at-sensor radiance[13]. Of course many technological improvements have been made, and many others have been discussed. For example, in the early 1990s the DOE engaged in discussions with the Landsat program Office on adding new capabilities to a future Landsat, specifically in improved thermal imaging capabilities, accurate atmospheric corrections, calibrations, and better spatial resolution. We were thwarted by several events. In September 1993 the Landsat 6 failed to reach orbit, leaving a strong potential for a data gap (Landsat 5 was already in orbit for nine years compared to a design life of three years). The Landsat Program Management was reorganized in 1994, with responsibility moving to NASA, NOAA, and the USGS[14]), and the Landsat 7 design converged to the ETM+. Contemporaneously, the DOE had unsuccessful discussions with NASA on a possible joint NASA / DOE multispectral imaging mission. The failure to find a suitable joint mission led to the DOE funding of the MTI system as a separate satellite.

Subsequently, the DOE worked with the Department of Defense (DoD) to explore options for launching the MTI satellite. We gained the support of the Air Force Space Experiments Review Board (AFSERB), which ranked MTI number one in 1996. Subsequently the Tri-Service Space Experiments Review Board decided to strongly support the launch of the MTI satellite, ranking it number two of thirty-one contenders. The Air Force Space Test Program then combined MTI with the High-energy X-Ray Spectrometer (HXRS) sponsored by the National Oceanic and Atmospheric Administration (NOAA) and developed by Space Devices, Ltd. of the Czech Republic [15]. This instrument is designed to help better understand solar flares and fits nicely in the MTI spacecraft bus.

The MTI satellite was placed into low Earth orbit March 12, 2000 by an Orbital Sciences Taurus rocket. Liftoff occurred at 0929 UTC (01:29 PST) from pad 576-East at Vandenberg Air Force Base in California. The first image was obtained on 28 March. After a three-month checkout phase, the MTI science phase started in June 2000.

2. SYSTEM DESIGN

We now discuss some specific design parameters of the Multispectral Thermal Imager. The interested reader may wish to consult more detailed discussions in this paper [16]. A complete list of MTI references is included in a paper presented at the 2000 SPIE Aerosense conference [17]. The following is a brief synopsis from these more extended papers.

The scientific basis for MTI lies in detailed physics-based modeling and analysis, which we reference as “end-to-end modeling and analysis” (commonly “EEM”). Briefly, we begin by defining targets and associated signatures of interest, translating those signatures into the MTI visual and infrared spectral domains. We then propagate the signatures through many representative atmospheres to a modeled payload, from which we compute electronic output signals. Those modeled signals are then used as inputs to analysis codes which provide retrievals for comparison to the original target signatures. We add realistic calibration capabilities to complete the EEM. Iteration then leads to self-consistent and buildable designs which are balanced with respect to atmospheric variability, instrument attributes, calibrations, and uncertainties in retrievals. As real hardware attributes become available, we substitute those for our estimated values. Finally, when the system operates one substitutes real data for the modeled data as input to the analysis codes. In the end, one hopes to fully validate the EEM with real performance, to further qualify the EEM as the basis for future measurement scenarios [17].

Key aspects of the design include selection of ground sampling distances, swath width, orbit parameters, spectral bands, signal-to-noise, and the calibration accuracy and precision requirements. The spectral bands address both the target signatures, as well as the ability to measure the key atmospheric variables which allow us to correct the observations for the state of the atmosphere at 20-meter resolution. We aimed for the lowest number of spectral bands, and the final design has fifteen, ranging from 0.4 to 11 microns. Signal to noise is driven by the self-consistent treatments in the EEM, as discussed above. Swath width is 12 km, which allows us to very readily image our selected sites and their surroundings with a relatively modest pointing accuracy of the satellite bus. Ground sampling distances of five and twenty meters are a compromise between a desire to obtain images with very fine spatial resolution, and the cost of the satellite systems[17].

Using the EEM we generated a basic set of attributes for MTI which the Engineering Teams translated into a satellite design. The payload has been described in some detail, with additional detail on the Optical Assembly and the Focal Plane Assembly. A simplified view of the MTI payload is shown in Figure 1. The Optical Assembly is a three mirror anastigmat, with a 0.36 meter primary and is temperature controlled with a design point of 270K. The aperture door has independent temperature controls, and is kept closed except during imaging to avoid contamination and to improve overall thermal control. The aperture door is also an essential part of the on-board calibration system: it is a clamshell design, which allows either full-aperture infrared calibrations, as well as permitting sunlight into the telescope via a diffuser panel. The Focal Plane Assembly (FPA) has three sensor chip assemblies, each one of which has sixteen linear arrays of detectors. (The array for band H is duplicated to allow adding and improve signal-to-noise.) Each linear array has its own spectral filter to select the appropriate wavelength coverage. The entire focal plane assembly is cooled to 75K by a mechanical cooler. In front of the FPA we see a calibration wheel which contains two blackbodies, two lamps, a retro-reflector, and an aperture; these sources are used before and after every image to characterize the FPA[17].

The payload was assembled and tested at Sandia, and was then trucked to Los Alamos for calibration in the Radiometric Calibration System (RCS) during the winter of 1998/1999. The facility [18] incorporates radiometric sources, spectral sources, spatial targets and mapping, as well as dynamic and static imaging. The radiometric calibration sources that were developed directly with the National Institute for Standards and Technology, NIST: indeed the sources received their final *radiometric* calibrations at NIST. The MTI has a number of operating parameters, which translates into a very comprehensive and lengthy data acquisition process. The MTI focal plane has some 17,000 active pixels (plus alternates!) incorporating three sensor materials (Si, InSb and HgCdTe) in 48 linear arrays. The focal plane was operated at several temperatures from 65 K to 90K, with two clock rates, and with integration times that are selectable, with typically eight values. Linearity and pixel mapping were specifically addressed. Radiometry for MTI in the infrared was referenced to nine blackbody temperatures between 250 and 350 K, and to five radiances in the visible and near-infrared. As stated above, the sources used were directly referenced (in radiometric terms) to NIST standards, providing unprecedented traceability for a satellite instrument. The goal of the ground calibration was to transfer the calibration to the on-board systems (aperture door and on-board calibration sources) as well as to understand various unavoidable imperfections in the MTI payload.

In the calibration laboratory, the MTI payload was operated close to the conditions that we anticipated encountering in space. For example, the payload structure was under temperature control at 270K, and the calibration sources near the focal plane assembly were used routinely. In addition to static imaging, the calibration facility provided some dynamic sequences that closely simulated the MTI angular rate over a target from space. Thus we have a very nice data set upon which to base our on-orbit calibration maintenance. Unfortunately, we operated in space for only seven months in this mode (see below).

The MTI payload is joined to a satellite bus produced by Ball Aerospace. The spacecraft bus is an aluminum frame and shear panel design structure standing approximately four feet high and weighing just under 140 kg. In addition to the structure and mechanisms for deploying solar arrays, Ball provided the electrical power and power distribution and the attitude determination and control subsystems (ADCS)[19]. Integration of the payload and the bus were conducted at Sandia, and the full spacecraft was then mated to an Orbital Taurus Launch Vehicle[20] at Vandenberg Air Force Base, California. The system was successfully launched at 01:29 am PST on 12 March, 2000 into a near-circular (580 km x 610 km) sun-synchronous orbit with a nominal 97.5 degree inclination and nominal 1 pm ascending node.

As launched, the overall satellite mass is 614 kg, with dimensions of 1.35m diameter and 2.6 m height in the launch configuration. Solar paddles deployed after launch to an in-light configuration depicted in Figure 2. Total power consumption averages 575 Watts, with the largest single power consumption due to the Stirling cycle cryogenic cooler which cools the focal plane and adjacent structures. The satellite is three-axis stabilized and maintains alignment of the solar paddles to the sun when not imaging. Navigation is by Global Positioning System augmented with sun sensors and gyros. The system does not have propulsion, so the orbit decays over time. The design mission life is a year, with a goal of three years.

The typical image taking sequence presently comprises a deep space look, followed by two looks at the scene (one near nadir and one off-nadir), followed by a space look. We nominally restrict image angles to be no more than +/- 20 degrees of roll, and +/- 50 degrees of pitch to maintain fine spatial resolution. Within this constraint, the system can access sites with an average revisit time of a week. The satellite operates as a push-broom imager, with the 48 linear arrays scanning a typical 12 km x 12 km image over the course of several seconds. Data are stored in an on-board memory, and forwarded via a five-meter diameter dish at the ground station at 8 Mbps. Satellite housekeeping data is linked at 2 kbps in the VHF, and commanding takes place at 2 kbps in the UHF, both using helix array antennas.

The MTI project requires excellent ground truth information to validate the performance of the system and analysis techniques in sixteen categories. The project has a ground truth team which has instrumented a number of suitable sites [21] with a selection of instruments. The full suite includes spectroradiometers, sun photometer, Fourier transform spectrometer, thermal imagers, infrared pyrometers, thermometers, blackbody references, weather station, tarpaulins, etc. We have agreements with a number of entities to obtain data collected by others. Additionally, we are engaged in some collaborative activities for cross-calibration and for algorithm validation.

3. OPERATIONS AND USER INTERFACES

The satellite is operated from a ground station at Sandia National Laboratory in Albuquerque, New Mexico, with occasional supplemental state-of-health data obtained from a Los Alamos operated ground station in Alaska. Tasking is determined based on operational requirements and a prioritized list of requested targets for both the DOE and the MTI Users Group. The down-linked data move automatically to the Data Processing and Analysis Center (DPAC) at Los Alamos, where automated processing occurs to calibrated imagery and data products. The staff at DPAC perform a variety of quality checks, and produce documentation and additional non-automated products. As of the time of writing, MTI had obtained imagery on some 240 different sites, with data processed on over 1250 individual imaging sequences. The level zero plus level one data (raw data through calibrated imagery) exceeds a terabyte, and dozens of CDROMs have been produced for our external US-government sponsored users.

Data products are defined in several levels, which correspond to the customary usage:
level zero: raw data and state of health;
level one: calibrated, registered, and geo-referenced imagery and data cubes;
level two: geophysical quantities for surface and atmospheric properties;
level three: time sequences;
level four: comparisons with models and advanced retrievals.

Level zero and most of level one processing is fully automated. One can obtain better registration of the 15 spectral bands and better joining of data from the three sensor chip assemblies by hand, and this is done for high value images. The DPAC operates a Web site, through which authorized users can see which products are already available, and place data requests.

Some sample imagery is shown in Figures 3, 4, 5, and 6.

Overall, the MTI satellite has been reliable, with a couple of unfortunate exceptions. In early April 2000, after just three weeks on-orbit, one of the two main on-board memory modules developed a short circuit. The operations team soon developed a modified method for memory management, and this failure has not impeded progress.

Of greater concern is the November 1, 2000 failure of the electronic controller for the telescope and calibration systems. As a consequence, the satellite now operates with the optical assembly aperture door open, with the on-board calibration wheel permanently in the open position, and with the optical assembly at a temperature 28K lower than designed with a larger temperature variation of +/- 2K. The focus adjustment is also disabled, with system focus stuck slightly away from the optimum position (a representative feature that used to be three pixels wide in the highest resolution visible band is now 3.5 pixels wide). With the door open, the system is no longer automatically protected from viewing the sun; we therefore require continuous operation of the Inertial Reference Unit and gyros. The open aperture door also partially blocks the S-band antenna, requiring more accurate pointing during down links. From an imaging and radiometry standpoint, we are pleased to have a data base of over seven hundred images and calibration sequences from before the failure. The team is using these data, plus data from more frequent vicarious calibrations and a space look before and after every image to produce well-calibrated imagery and data products.

Despite these on-orbit issues, the MTI shows excellent repeatability, which is essential for the more complicated analyses that the team now undertakes.

4. SUMMARY

The Multispectral Thermal Imager satellite fills a new and important role in advancing the state of the art in remote sensing sciences. Initial results with the full calibration system operating indicate that the system was already close to achieving the very ambitious goals which we laid out in 1993, and we are confident of reaching all of these goals as we continue our research and improve our analyses. In addition to the DOE interests, the satellite is tasked about one-third of the time with requests from other users supporting research ranging from volcanology to atmospheric sciences.

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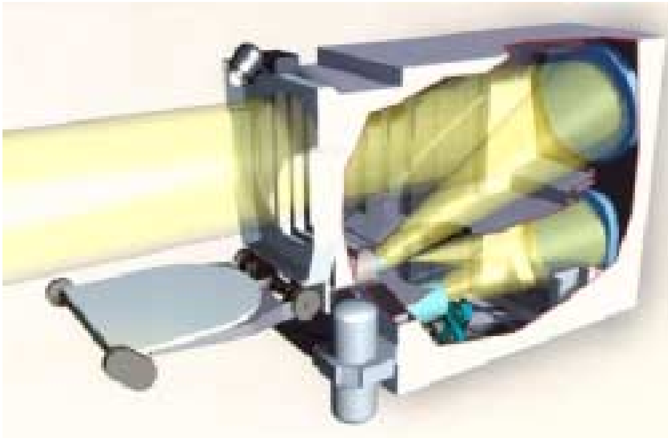

Fig 1: Simplified view of the MTI optical and calibration system.

Figure 2: Artist's concept of the MTI flight configuration.

Figure 3: MTI view of the tip of Manhattan Island, New York. This is a false color composite using bands B, C, and D, which renders vegetation in red.

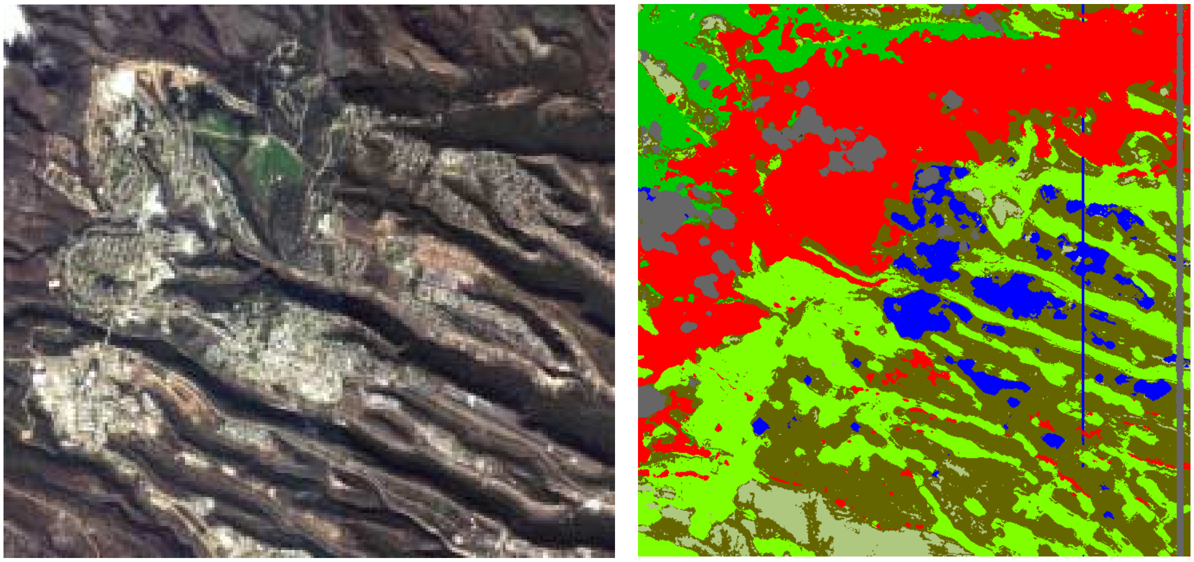

Figure 4: True color image and ground cover classification of Los Alamos, NM, after the Cerro Grande fire.

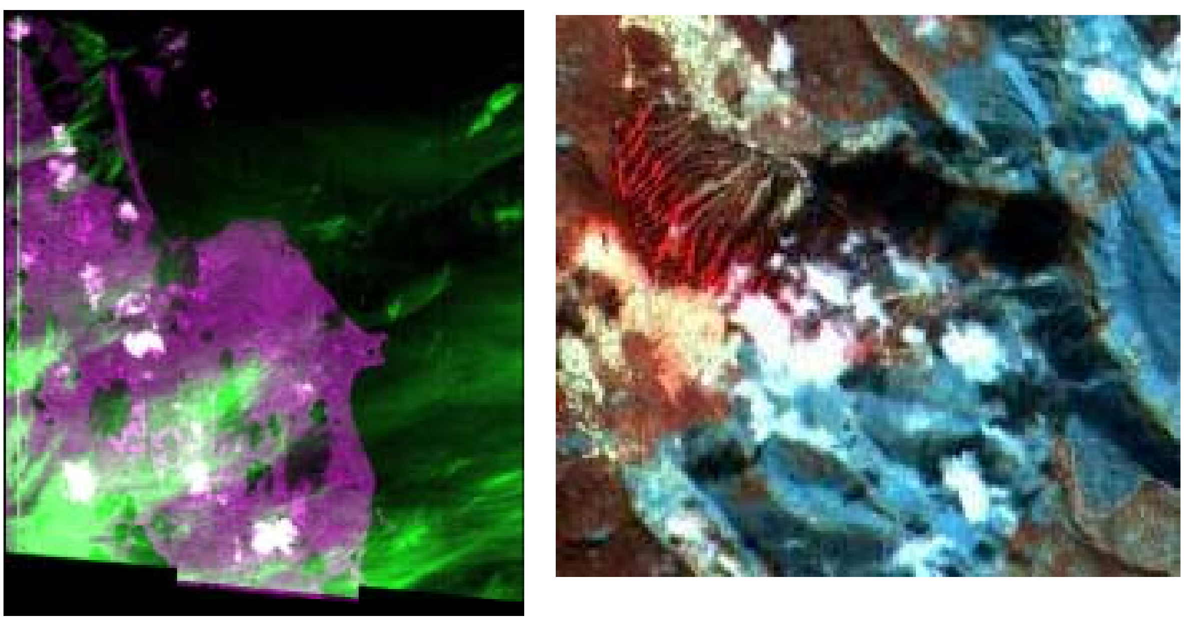

Figure 5: Demonstration of Cirrus cloud detection and snow / cloud discrimination.

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